Acousto--defect interaction in irradiated and non--irradiated n+--p- silicon -structures

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Abstract

The experimental investigation of ultrasound influence on the electrical characteristics of silicon n+-p--structure has been carried out. The ultrasound induced effects in silicon structures, which have been exposed to reactor neutrons or 60Co gamma radiation, were studied too. It has been found out that the ultrasound loading of n+--p--structure leads to reversible change of shunt resistance, carrier lifetime, and ideality factor. Acoustically induced alteration of the ideality factor and the space charge region lifetime depends on irradiation considerably. The models of coupled defect level recombination, Shockley--Read--Hall recombination, and dislocation--induced impedance were used to describe the obtained results. The observed phenomena can deal with the increase of distance between coupled defects as well as an extension of carrier capture coefficient of complex point defects and dislocations. The results show that divacancy and vacancy--interstitial oxygen pair are effectively modified by ultrasound in contrast to interstitial carbon--interstitial oxygen complex.

Introduction

It is well known that ultrasound (US) can effectively interact with defects. As a defect engineering tool, US has the following advantages:

(i)~locality of action due to predominant absorption in the regions of lattice periodicity deviation;

(ii)~selectivity of influence, which depends on acoustic wave (AW) polarization and type;

(iii)~possibility to transform the defect system by applying US resonance frequency;

(iv)~capability of reversible effect in case of low intensity AW.

In piezoelectric semiconductors, acousto--defect interaction (ADI) is mainly determined by the electric field that accompanies the vibration wave propagation. However, ADI is also observed in such non--piezoelectric crystals as silicon, the basic material in microelectronics. Thus, it was experimentally observed that US can cause atomic diffusion, transformation of native and impurity defects, modification of interior surface states and appearance of new defects in Si structures, which determines most of semiconductor device characteristics. In particular, ADI governs the variation of tunneling, generation--recombination and thermionic emission currents in silicon barrier structures.

The change of population of impurity oscillator levels, the displacement of impurity atoms with respect to their surroundings, the decrease of diffusion activation energy, the local temperature increase caused by point defect clusters as well as US absorption by dislocations are believed to be the main mechanisms of elastic vibration--defect interaction in non--piezoelectric crystals. However, to the best of our knowledge, there is no a comprehensive ADI theory for silicon structures suggested so far, the lack of experimental researches focused on acoustically induced (AI) effects being one of the main reasons

The defects in silicon structures are not all acoustically active and can remain unmodified under the action of ultrasound. The ADI efficiency depends on defect type and structure. Thus, the force acting on point defect in the crystal under US loading (USL) is determined by the relaxation of defect volume. The alterations of semiconductor defects are most widely//often produced by using the well-studied irradiation method. On the one hand, high--power US treatment of irradiated silicon structures has been shown to result in residual changes in structure properties. This effect deals with AI annealing of radiation defects (RDs). On the other hand, irradiation can be the reason of reversible AI initiation, which is caused by the formation of acoustically active RDs. Unfortunately, there are but a few (всего лишь несколько)// there are few reports(мало сообщений) on acoustically driven phenomenon in irradiated silicon structures.

The aim of our work is to investigate experimentally the AI electrical characteristics variations that take place in non--irradiated and irradiated n+--p-Si structures. For this purpose, the samples were irradiated by reactor neutrons and 60Co--gamma source rays. It is supposed// expected that γ--rays introduce predominantly VOi complexes, whereas neutrons mainly create vacancy clusters, disordered regions and CiOi complexes. Our work presents the distinction between AI effects in silicon structures with different RDs. The intensity of the US applied was below the level of irreversible defect subsystem modification, which can deal with?? a new defect formation, RDs annealing or a long distance (a many interatomic distance) diffusion. As a result, the complete recovery of characteristics was observed after AW propagation had stopped.

To describe the processes in space charge region (SCR) and in the diode base as well as to study shunt resistance, we used the models of coupled defect level recombination, Shockley--Read--Hall (SRH) recombination and dislocation--induced impedance, respectively. The models of coupled defect level recombination, Shockley--Read--Hall (SRH) recombination, and dislocation--induced impedance were used to describe the processes in space charge region (SCR), in the diode base, and shunt resistance, respectively. The observed (перечисленные выше?) AI phenomena are accounted for in terms of defect interaction with AW strain field. The interaction of defects with AW strain?? field was recruited to explain the observed AI phenomena. Our research not only provides a better understanding of ADI but could also facilitate the development of acoustically controlled devices or radiation sensors.

Experimental and calculation details

N+-p--Si structure was fabricated//produced from 2 inch (300~μm) thick p--type boron doped Czochralski silicon wafer with <111> orientation and resistivity of 10~Οcm. The2 inch (300~μm thick) p--type boron doped, <111> orientation, Czochralski silicon wafer with resistivity of 10~Οcm was used for fabrication of n+-p--Si structure. The n+ emitter with carrier concentration of about 1019 cm-3 and thickness of 0.5~μm was formed by implanting phosphorus. The front and rear aluminium electrodes were deposited by screen printing before rapid annealing. The samples used in the experiment were cut from the central part of the wafer and had the area of 2 cm2. The samples were irradiated by reactor neutrons or by 60Co γ--rays. The doses D, fluences Φ, and sample labels are listed in Table Ι. To determine D and Φ correlation, the data from [44,45] were used. The non--ionizing energy losses (NIEL) for neutron and γ--60Co are also shown in Table Ι. Since the displacement damage effect is characterized by Φ NIEL, a similar damage was expected in the investigated samples as well. To avoid the impact of long--term annealing, which is typical to neutron damaged structures, the irradiated samples were stored at room temperature for 5 years before the measurements.

The dark forward current--voltage characteristics I--V of the samples both with and without USL were measured over the temperature range 290--340~K. The temperature was controlled by differential copper--constantan thermocouple. Some of the obtained curves are shown in Fig. 1.

The double--diode model of n+--p structure I-V characteristics is expressed in the following form:

(1)

where

ISCR describes/shows/reflects the overall SCR recombination, I\_base is closely related to the recombination in quasi-neutral region, I\_sh is the shunt current, A is the sample area, n\_i is the intrinsic carrier concentration, tau\_g is the SCR carrier lifetime, d is the SCR thickness:

(5)

ε is the permittivity (11.7 for Si), p\_p and n\_n are the majority carrier concentration in the p-- and n--type regions, E\_g is the semiconductor band gap, N\_c and N\_v are the effective densities of states in the conduction and valence bands; n\_id is the ideality factor, R\_s and R\_sh are the series and shunt resistances, mu\_n and tau\_n are the electron (minority carrier) mobility and lifetime in the diode base.

We used Eqs. (1)-(5) to fit the experimental data taking tau\_g, tau\_n, n\_id, R\_sh and R\_s as fitting parameters. Also, we used the known temperature dependences of n\_i, E\_g, and mu\_n. In the result, we obtained extremely good fit to the experimental data --- see Fig. 1. In particular, for all the samples the value of R\_s was found to be about 1 Ohm. The broken line in Fig.1(a) shows an example of the calculated contributions of I\_SCR, I\_base and I\_sh to the total current.

In case of USL, the transverse AWs with frequency of 4.2~MHz, which were exited with by using piezoelectric transducer, were applied to the samples at the base side in [111]--direction. The US intensities W\_US, amplitudes? of lattice deformation xi\_US and lattice atom displacement u\_US are listed in Table II. As reported previously, It was reported previously that (ссылки не будет? Тогда красный вариант) the characteristic time of change in silicon structure parameters under US action did not exceed 2 10^3 s. In order to wait till the AI transitional period the following experimental procedure was used. When USL started, the sample was first exposed to at room temperature for 60~min and then, while the sample was heated, we started measuring I-V. In order to avoid the effect of piezoelectric field on I-V characteristics, the piezoelectric transducer was shielded.

Fig. 2 illustrates the reversibility of AI effects. The time interval between USL initiation and "during" measurement was longer than 60~min, the time interval between USL termination and "after" measurement was about 24~h. The data for nSC and g6SC are similar to those presented for iSC and g7SC.

Не понимаю связи с предыдущим параграфом The non-linear fittings were performed by using the differential evolution method.

Results and Discussion

*Space charge region*

The parameters of I-V characteristics associated with//cause by// that deal with SCR phenomena are n\_id and tau\_g. The temperature dependences of ideality factor and SCR carrier lifetime are shown in Fig. 3 and Fig. 4 respectively.

As seen from Fig. 3, the ideality factor decreases with temperature increase and the plot n\_id vs $1/T$ is close to linear. Thus, dependence n\_id(T) can be expressed as

(6)

The thermoactivated growth of SCR lifetime is observed over the explored temperature range --- see Fig. 4. The temperature dependence of tau\_g is sufficiently (достаточно)? described by the equation

(7)

The values of T\_id and E\_tau found/calculated determined for both non--irradiated and irradiated samples under USL as well as without it are listed in Table III.

We would like to stress that

(i) irradiation leads to T\_id and E\_tau changes, g6SC's characteristic temperature of ideality factor and SCR lifetime characteristic energy are closely related to those of g7SC under similar conditions;

(ii) USL affects n\_id and tau\_g values; the absolute AI changes of ideality factor Δn\_id=n\_idUS-n\_idin and the relative AI changes of SCR lifetime ε\_tau=(tau\_gUS-tau\_g,in)/tau\_g,in (where subscripts ''US'' and ``in'' indicate the values obtained at the same temperature with and without USL respectively) are listed in Table IV;

(iii) Δn\_id and ε\_tau vary with W\_US enhancement, whereas T\_id and E\_tau values practically do not depend on US intensity;

(iv) USL leads to the increase in both T\_id and E\_tau in γ--irradiated samples (see Fig. 3(b) and Fig. 4(b)), but this effect is not observed in non--irradiated and neutron--irradiated samples (see Fig. 3(a) and Fig. 4(a));

(v) Δ n\_id and ε\_tau have an opposite sign for non--irradiated and irradiated samples (for SCg6 - not in the whole temperature range);

(vi) ideality factor is varied by USL more effectively in irradiated samples.

For the purposes of our analysis// present consideration it is important to discuss the recombination mechanism in SCR of the investigated samples. According to classical SRH theory, the ideality factor must be less than 2, and tau\_g temperature dependence is expected to be described by the relation tau\_g=1/2 (where σ\_n and σ\_p are the electron and hole capture cross sections (CCSs) and the energy level of the recombination center, E\_i is the intrinsic energy level). In our case, n\_id is greater than 2 and tau\_g increases with temperature. Therefore, SRH theory cannot be applied in our case. Several attempts to account for large n\_id value have been made by using different (разные, отличающиеся друг от друга)// various (разнообразные, всевозможные)models. However, all the observed features of SCR recombination (large ideality factor value, independence on light intensity, dependence on temperature as well as short carrier lifetime // carrier lifetime small value) can be explained by the model of coupled defect level recombination (CDLR) only. This mechanism provides a rapid direct charge transfer between defect levels. The phenomenon was first observed experimentally, after which it was recruited to explain the process in semiconductor diodes.

According to CDLR model, recombination is the result of carrier exchange between two defect levels and crystal bands. In particular, it is supposed (предполагается)//proposed (предлагается) that the recombination rate is dominant at the sites// is dominated by the sites where acceptor--like defect is coupled with donor-like defect. In a simplified case, when there is no carrier exchange between the donor level E\_tD and valence band, as well as between the acceptor level E\_tA and conduction band, the recombination rate R can be expressed as

(8)

Where R\_DA is a coupling parameter, N\_D and N\_A are the densities of donor and acceptor--like defects, σ\_nD and σ\_pA are electron CCS of donor and hole CCS of acceptor, v\_th,n and v\_th,p are thermal electron and hole velocities, n\_D,A, p\_D,A, and ε depend on E\_tD, E\_tA and the level degeneracy factors. Sincе tau\_g~ R-1, the last three values are expected to provide thermoactivated behavior of SCR lifetime. Unfortunately, the equation does not account for the functional relation between I-V characteristics parameters and attributes of defects taking part in CDLR.

According to Steingrube et al., SSC for defect in a pair differs from that for an isolated defect and depends on the distance r between donor and acceptor:

(9)

where C\_nD and C\_pA are constant values. Besides, R\_DA is proportional to the overlap integral of the defects wave functions. If both defects are characterized by H--like radial--symmetric wave function, and equal Bohr radius a\_0, the following expression can be used:

(10)

In our opinion, the observed reversible AI n\_id and modified tau\_g modifications are induced by donor--acceptor distance alteration in the samples under USL. Therefore? //In fact //Really, according to data [3], the force acting on the point defect during USL can be expressed as

(11)

where Γ is the bulk elasticity modulus, ΔΩ\_d is the crystal volume change per defect, χ is the crystal lattice deformation, and AW propagates along z axis. ΔΩ\_d > 0 for the interstitial atoms and substitutional impurities with ionic radius exceeding the ionic radius of matrix atoms ΔΩ\_d > 0, whereas for the vacancies and substitutional impurities whose ionic radius is smaller than that //the ionic radius of matrix atoms ΔΩ\_d < 0. Therefore, a point defect vibrates under USL, so// and the oscillation amplitude and phase are determined by both the defect character and AW intensity.

The simplest model, which is shown in Fig. 5, gives the following qualitative conclusion. Initially, donor and acceptor are separated by distance r\_in, and axis X is drawn through the point defect initial positions. Under USL, the defects would vibrate with amplitudes u\_D and u\_A. The vibration axis coincides with AW displacement direction and forms angle h with X--axis. Depending on χ\_US, defect elastic strain (ΔΩ\_dD and ΔΩ\_dΑ) and defect coupling the defect vibration amplitudes can have different values.// The defect vibration amplitudes depend on χ\_US, defect elastic strain (ΔΩ\_dD and ΔΩ\_dΑ), defect coupling and may have different values. The donor--acceptor distance r\_US, according to the model, depends on time t:// According to the suggested model, the donor--acceptor distance in the sample under USL r\_US depends on time t:

(12)

where ω is the US cyclic frequency and δ is the phase shift between donor and acceptor vibration.

We use Eqs. (11)-(12) to estimate AI relative changes of CCS εσ=[σUS-σ(r\_in)]/\σ(r\_in) and coupling parameters ε\_RDA=[R\_DA,US-R\_DA(r\_in)]/R\_DA(r\_in), where σ and R are averaged over the AW period T\_US:

(13)

In this estimation, the relaxation time in CDLR sub--system is assumed to be considerably shorter than T\_US, so we apply the previously used value a\_0=3.23 nm is applied. In addition// Besides, the chosen u\_D and u\_A values are commensurate with u\_US. However, it should be is taken into account, that the displacement of point defect without covalent bond could exceed a matrix atom displacement. Finally, no US absorption by defect is assumed. In this simple case, δ is equal to 0 if (ΔΩ\_d D ΔΩ\_d A>0), or to 180 if (ΔΩ\_d D ΔΩ\_d A<0). In addition, ε\_RDA dependence on u\_D and u\_A is only determined by |u\_D-u\_A| (δ=0 case) or |u\_D+u\_A| (δ=180 case). Moreover, these dependences are identical in both cases. The typical results of simulated coupling parameter changes are shown in Fig. 6.

Обозвать словами эту величину, т.к. это начало абзаца ε\_σ depends on oscillation amplitudes with similar features and does not depend on φ:

(14)

where``+'' and ``-'' correspond to δ=180 and δ=0 respectively, K\_USDA characterizes defect couple--ultrasound interaction and depends on properties defects as well as crystal matrix. Eq. (15) takes into account that u\_D,u\_A ~χ\_US~W\_US.

It is worth keeping in mind that CLDR current flows locally in the locations of extended defects. At the same time, the dislocations are often located// situated perpendicularly to p-n junction plane in the SCR region, and the investigated samples are not an exception (see Section IIIC). If CDLR in the dislocation locations is assumed, then the dislocations with edge component will//should// would affect the pair spatial orientation. Thus, the axis of donor--acceptor pair with ( ΔΩ\_d D ΔΩ\_d A>0)$ should be predominantly parallel to dislocation line, whereas the axis of a pair of coupled defects with ΔΩ\_d D ΔΩ\_d A<0 should make a right angle with dislocation line. As AW displacement is parallel to p-n junction plane, the cases of the most exciting interest are the following:

δ=0...

In other words, all the curves in Fig. 6 can be realized if defect volume relaxation of donor--like defect has the sign opposite to that of acceptor--like defect. Morover, only squares should //have to be under consideration in case ifΔΩ\_d D ΔΩ\_d A>0.

Taking into account the experimental results and the estimation suggested by our model:

(i) E\_tau and T\_id$ are mainly determined by couple component energy levels. The alteration of E\_tau and T\_id for nSC, g6SC, and g7SC in comparison with iSC testifies to the change of defect (donor, acceptor, or both) which takes part in CDLR after irradiation. And g6SC defect is coincident with g7SC defect and differs from neutron--irradiated sample defect.

(ii) USL causes donor--acceptor distance change and results in ε\_σ and ε\_RDA, which increase with W\_US.

(iii) Acoustically induced E\_tau and T\_id modification, which is observed in g6SC, and g7SC only, testifies to rebuilding γ-induced RD, i.e., γ--induced RD is conﬁgurationally bistable (or metastable) and transforms from ground state to another? under US action. Similar AI defect variations were also reported previously.

(iv) ε\_σ sign is immutable --- see Eq. 15, whereas ε\_RDA sign can vary for the pair with opposite relaxation volume component (see Fig. 6). Therefore, Δ n\_id and ε\_tau signs change, which is the evidence of transformation from (ΔΩ\_d D ΔΩ\_d A>0) to (ΔΩ\_d D ΔΩ\_d A<0) after irradiation. The transformation is confirmed by the enhanced efficiency of US action on defects// by the rise of US influence efficiency in the irradiated samples. In fact//Really, in the case of (ΔΩ\_d D ΔΩ\_d A<0) the US efficiency is determined by the sum of pair component displacements, whereas in the contrary case --- by their difference. Conceivably, both donor and acceptor are interstitial-type defects ??//of interstitial--type in non--irradiated sample, and one of pair?? components is a vacancy-type defect//of vacancy--type in irradiated samples. The defect configurations are discussed below, in Section IID.

*Quasi--neutral region*

Base lifetime mirrors the processes which occur in quasi--neutral region of p-n--structure. Fig. 7 shows tau\_n behaviour in the explored temperature range. As expected, the minority carrier lifetime increases as the temperature grows, and at 320~K, tau\_n values comprise 2-5 μs for different samples, which correspond to 80-130 μm range of diffusion lengths. In our opinion, the observed tau\_n dispersion is caused not by irradiation, but rather deals with sample--ancestor wafer inhomogeneity, which is often the case.

In fact Really, the reduction in irradiation induced lifetime is described by the Messenger–-Spratt equation:

(16)

where tau\_n0 is the minority carrier lifetime in non--irradiated sample and K\_tau is a lifetime damage--constant. The known K\_\tau values and estimated changes in reciprocal base lifetime K\_tauΦ are shown in Table V. As seen from the table, the estimated values of radiation--induced tau\_n-1 change comprise 8-17, 4, and 29 % of its values measured for samples nSC, g6SC and g7SC, respectively, so this cannot explain the dispersion observed experimentally. At the same time, the calculated lifetime changes K\_tauΦ are in quite a good agreement with those expected from RDs production --- see Section ΙΙΙD.

Base lifetime can be expressed as follows:

(18)

Where tau\_bb, tau\_CE and tau\_SRH are the lifetimes of band--to—band recombination, Coloumb--enhanced Auger recombination and SRH recombination, respectively. The calculation shows that tau\_bb=14 s, tau\_CE=7 s and (здесь что-то пропущено?) can be neglected. In case of low injection level and single recombination centre, SRH lifetime is described by Eq. (10). If there are several centers of recombination, the following equation should be applied

(19)

Where M\_d is the total number of centers, tau\_n,i characterizes lifetime due to recombination by i-th defect, N\_d,i and σ\_n,i are the concentration and electron CCS of i-th defect, respectively.

Fig. 7 shows that USL results in tau\_n decrease. Relative AI changes of reciprocal base lifetime ε\_tau n=(tau\_n,in-tau\_nUS)/tau\_nUS are listed in Table IV. As AI changes are?? is reversible, this effect, in our opinion, deals with increase of σ\_n under US action. Following the empirical relation proposed by Ref. 65, we assume that Eq. (11) is valid for a complex point defect as well. In this case, however, r is the distance which separates the components of a/the? complex. According to the model suggested in Section IIIA, USL leads to r variation and σ\_n change in line with Eq. (15). In case of CDLR, AI change of donor (or/and acceptor) SSC??? is supplemental to the variation of both coupling parameter and couple distance, but only the change of SSC determines the AI variation of the base lifetime.

However, not every defect effectively takes part in AID. If M\_dAA and M\_dnonAA are the total numbers of acoustically active (AA) and non--AA (non-AA) (это для однородности) centers, Eq (18) for tau\_n-1 under USL and without it takes the following shape

(20)

By using Eq (15), ε\_taun is transformed as follows

(21)

where K\_USeff characterizes ADI in the sample and depends on the concentration of both AA and non--AA centers

(22)

K\_US,j deals with j--th defect--ultrasound interaction.

The obtained dependences of ε\_taun vs W\_US are shown in Fig. 8. The linearity of these dependences prove the correctness of our assumptions. The obtained K\_USeff values are listed in Table V. Non--monotonic K\_USeff alteration with γ dose is discussed in Section IIID.

*Shunt resistance*

Fig. 9 shows the shunt resistance over the explored temperature range. As seen from the figure, the irradiation results in R\_sh decrease. Also, the R\_sh temperature dependence behavior is changed in γ-exposed samples??. In particular, the shunt resistance decreases with the temperature growth, whereas in g6SC and g7SC the increase of R\_sh vs T is close to linear at//in the vicinity of//nearby 293~K //close to linear increase of R\_sh vs T is observed in g6SC and g7SC at 293~K neighbourhood. It should be noted that R\_sh axis is logarithmic in Fig. 9(a) and linear in Fig. 9(b).

The shunt resistance is known to occur in p--n structure due to several reasons. It can be caused by aluminum particles, macroscopic Si3N4 inclusions or inversion layers at precipitates. In the course of firing??, Al particle can penetrate into the sample creating a p+--doped region around itself?// it, which compensates the emitter and remains// stays in ohmic contact with the base. Inversion layers and Si3N4 inclusions occur mainly in multicrystalline silicon cells and cannot cause shunt resistance in the investigated samples. Dislocations, however, which intersect the junction, are generally held responsible as a possible source of ohmic current. In our opinion, both aluminum particles and dislocations are present in the investigated structures, so the overall shunt resistance can be expressed as

(23)

Where R\_shAl and $R\_shdis deal with aluminum particles and dislocations respectively. The linear temperature dependence of metal particles R\_shAl is suggested:?

(24)

where R\_293Al is the shunt resistance at 293 K and α is the resistance temperature coefficient.

According to the model of dislocation--induced impedance of photovoltaic detector suggested by Gopal and Gupta, R\_sh,dis can be given by:

(25)

with

(26)

where E\_dis is the energy level which significantly contributes to the dislocation recombination current, U\_s is the potential at the surface of the dislocation core, ρ\_dis and A\_dis are the dislocation density and surface area, respectively, K\_n and K\_p are the probabilities for electrons and holes capture by the dislocation states, N\_dis is the density of surface states at each dislocation. Eq. (23) is true for the simplified case of K\_p=K\_n.

Обозвать словами эту величину, т.к. это начало абзаца α was estimated from data on g7SC. The obtained value 8.3 K is not far from resistance temperature coefficient of bulk Al (4.3 K). To fit the experimental data for R\_sh we used Eqs. (21)-(23). As the fitting parameters, R\_293Al, (E\_dis-E\_i), U\_s, and σ\_dis were taken. It has been found that the experimental data are in good agreement with the fitting curves (see Fig. 9) for values (E\_dis-E\_i)=0.46 eV and U\_s=5 eV, which were independent of irradiation and USL. The obtained value of (E\_dis-E\_i) corresponds to the carrier activation energy 0.10 eV and is comparable with the activation energy of dislocation levels 0.08 eV, which was earlier reported [24] in Cz--Si:B too [23] (непонятно место ссылок).

The obtained values of R\_293Al and σ\_dis are given in Table III. R\_293Al does not depend on USL and increases as the irradiation уровень, не интенсивность ? level is increased. In our opinion, R\_shdis is smaller than R\_shAl in iSC. The irradiation facilitates (способствует)//leads to the formation of vacancies as well as Al diffusion out of the electrodes. As a consequence, the number of Al particles grow, R\_shAl decreases and becomes the key factor influencing //contributing in //determining of the overall shunt resistance. Al diffuses more effectively in the samples exposed to γ--radiation due to a more uniform distribution of irradiation--induced single vacancies.

Dispersions of σ\_dis and tau\_n correlate on samples set??. Hence it??? deals with wafer inhomogeneity too. USL causes //leads to σ\_dis increase, relative AI changes ε\_σdis=(σ\_dis,US-σ\_dis,in)/σ\_dis,in are shown in Table IV. In our opinion, this is caused by A\_dis augmentation. Namely, the dislocation core atom displacement is normal to the current direction. As a result, the carriers are captured by dislocation levels from enlarged volume. Therefore, the effective surface area increases and R\_shdis decreases due to// under US action.

*Defect type speculation*

Lifetime killers in boron--doped Czochralski--grown Si are boron--oxygen related (BO) defects, iron--boron pairs (or another Fe--related trap in the n+-p--junctions), and oxide precipitates. The first two defects are sensitive to intensive illumination at room temperature. To determine the major recombination center in the investigated samples the following experimental procedure was used. A non-irradiated sample was light soaked under illumination by halogen lamp (2 Suns) at approximately 305 K. The illumination time varied from 1 h to 8 h. After illumination was terminated, the sample was exposed to room temperature in the darkness for 5 h. Over this time period, I-V characteristics were measured with the interval 10—15 min in order to determine the kinetics of the ( I-V??) parameters at room temperature. To estimate the permanent light--induced change, the measurements of I-V characteristics were performed in 48 h after illumination. After the total// accumulated time under illumination ran up to 15 h, the iSC was annealed at 200 C for 10 min in darkness, after which the measurements were carried out at room temperature. Then the illumination and measurements were repeated.

Intensive light is known to cause permanent transformation of BO defects and considerable decrease of minority--carrier lifetime (as low as 10 \% of initial value at long term illumination). Annealing at 200 C for 10 min in the darkness results in both recovery of state and readiness to light--induced degradation of BO defects // in both BO defects state recovery and readiness of?? light--induced degradation. Fig. 10 shows the changes of structure parameters in comparison with those prior to illumination. As seen from the figure, illumination does not result in considerable permanent change of either of the tau\_g, tau\_n, n\_id before as well as after annealing. Therefore, BO influence on recombination can be neglected in both the SCR and base.

At the same time, a vast majority of impurity iron is included in iron--boron pairs. FeiBs can be readily dissociated under intense illumination to release interstitial iron, which result in lifetime changes. In the darkness, FeiBs is repaired //recovers// repairing takes place and Fei concentration decreases according to

(27)

where N\_Fe0 is the concentration immediately after illumination, and N\_Feeq is the equilibrium concentration which remains for a long time after dissociation; the characteristic time of recovering//repairing tau\_rep depends on the doping level

(28)

E\_DFe=0.68 eV is the activation energy of Fei diffusion.

It was found that n\_id increased (by about 0.03) and tau\_g decreased (by about 10 \%) immediately after illumination --- see Fig. 11(a), but the changes vanished gradually. We supposed that tau\_g and n\_id evolutions could be described by the expressions similar to Eq. (25). The obtained Eq. (26) was used to calculate the characteristic time, and the fitting lines are presented in Fig. 12(a). The fittings with E\_DFe=0.68 eV are in good agreement with the experimental data. Hence, it is evident that iron--boron pairs take part in SCR recombination. At the same time, electron and hole CCS of Fei are 1.7 and 0.04 times as much as those of FeiBs. A small tau\_g alteration (by about 10 \%) caused by light is the evidence of the supporting role of iron--boron pair in SCR recombination. Furthermore, since tau\_n does not depend on illumination (see Fig. 12(b)), FeiBs does not influence the base lifetime.

Thus, a conclusion can be made that oxide precipitates are number one agents//factors in SCR and base recombinations. According to Murphy, there exist at least two independent oxide precipitate related defects. These defects have σ\_n/σ\_p=157 and σ\_p/σ\_n=1200, respectively, which is suitable for CDLR. These//The above facts allow us to conclude that the defect responsible for AI phenomena in nSC is mainly oxide precipitate.

In foreseeing RD type, it is worth keeping in mind doping level, oxygen concentration and irradiation dose in mind. In our case (Czochralski, oxygen--rich, 717 cm3, p--Si with boron concentration 1015 cm3 and low dose) it is expected that CiOi, vacancy clusters Vn (divacancy V2, trivacancy V3, ...), and VOi are produced mainly by neutron irradiation, while CiOi and VOi - by γ--rays. The RD concentration N\_tRD is proportionate to Something that is **proportional** (1) forms a whole with other quantities, or (2) is considered quantitatively with respect to something else. ***Proportionate***means in due proportion. The distinction is subtle, but proportionate describes something that is made that way by an active agent, and it often describes quantities that are difficult to measure. Proportional doesn’t necessarily involve an active agent, and it is the preferred term where actual measurements are concerned dose, the known introduction rate for neutron η\_n and gamma η\_γ irradiation in Cz--Si are shown in the Table VI. The expected values of N\_tRD for the investigated samples are listed in Table VI as well.

The other defects that can be created by irradiating silicon are I\_p--center, bistable donor (BD), B\_iO\_i and C\_iC\_s. But I\_p--center and BD are characterized by small introduction rate. For example, the expected concentration of BD is only 1 1010 cm3 in nSC and g7SC. The lack of B\_iO\_i in the investigated samples deals with low boron concentration. The formation of C\_iC\_s is suppressed in oxygen--rich crystal and, what is more, C\_iC\_s is not an active recombination center.

The influence of RD on base lifetime could be estimated by Eq. (18) taking into account the fact that VO\_i is a recombination center which is not active // is not an active recombination center in p--Si. The estimated tau\_nRD for CiOi, V2 and V\_3 are shown in Table VI. As seen from the table, tau\_n is effected mainly by CiOi and vacancy clusters in $\gamma$-- and neutron--irradiated samples, respectively. It should be noted, that nSC, g6SC and g7SC sums of tau\_nRD are in quite good agreement with experimentally obtained? K\_tauΦ// K\_tauΦ values.

We shall now consider K\_USeff for non--irradiated sample assuming M\_dAA=1 and M\_dnonAA=1. We shall also assume that US interactions with CiOi and Vn are described by K\_USCO and K\_USV, respectively. Then Eq. (20) gives the following expression for K\_USeff in nSC and irradiated samples:

(34)

tau\_AA is the base lifetime of the sample, where non-radiative AA defect with K\_USAA is present only.

For the analysis the following Two extreme cases are appropriate opportune. In the first one, non--AA defects are distributed uniformly across the wafer, and AA defects define a distinction of (tau\_nin-K\_tauΦ) values in different samples. In the second one, the distribution of non--AA defects is not uniform, and tau\_ninAA is identical for iSC, nSC, g6SC, and g7SC. However, in the first case (as well as in case of M\_dnonAA=0), the experimental values of K\_USeff lead to unreal (negative) values of K\_USj. In the second case, Eq. (41) and the data from Tables VI and V, give the following array equations:

(45)

where tau\_ninAA in 104 s. These equations are valid for K\_USAA=10 W, K\_USV=42 W, K\_USCO=0. Since tau\_nin <1.83, K\_USAA>5 cm2. Thus, the observed change in base lifetime is caused by AI modification of the same defects (most likely oxide precipitates) in both non--irradiated and $\gamma$--irradiated samples. This effect is enhanced// added by alteration of AI divacancy in neutron--irradiated samples. In other words, CiOi is a non--AA defect, whereas V\_2 is an AA defect.

With regard to SCR recombination, in our opinion, under US action, tau\_g and n\_id in non--irradiated samples depend on// are affected by the modification of coupled oxide precipitate related defects. As assumed in Section IIIA, the AA radiation defects with ΔΩ\_d<0 take part in CDLR in irradiated samples. Divacancy is quite suitable explanation for AI influence on tau\_g and n\_id in nSC, but in γ--irradiated samples a bistable (or metastable) defect is expected. Few??? such defects with ΔΩ\_d<0 are known in Si, viz VO\_2, V\_3 and VO\_i. VO\_2 is formed appears after 300 C annealing of irradiated crystal, V\_3 is not typical for γ-60Co exposed silicon, while VO\_i is largo manum produced and can take part in CDLR around n^+-p interface in g6SC and g7SC. The metastable state commonly observed at low temperature is remarkable for large oxygen--vacancy distance and deeper energy level. The volume change of entire complex is negative, whereas for the complex component, ΔΩ\_d<0 and ΔΩ\_d>0. Hence, under the assumption made, VO\_i is a favorable pair for AI alteration of distance between the components and therefore, can be transformed into metastable configuration by USL, which causes changes in both T\_id and E\_tau.

Conclusion

The influence of ultrasound on I-V characteristics of non-irradiated silicon n^+-p--structures as well as silicon structures exposed to reactor neutrons or 60Co gamma radiation have been investigated experimentally. The investigation has revealed acoustically driven reversible decrease in both the minority carrier lifetime and shunt resistance in the structure base. The effect is intensified in the irradiated structures. The analysis has shown that these effects are caused by acoustically induced increase in carrier capture coefficient for point or extended defects. It has also been found that ultrasound loading leads to reversible modification of SCR carrier lifetime and ideality factor. The changes are opposite in sign in non--irradiated and irradiated structures. The qualitative model of the observed phenomenon, which is based on the increase in the distance between coupled defects or between complex defect components// defect complex components due to ultrasound action has been suggested/developed and analyzed// was considered. According to the model, interstitial carbon--interstitial oxygen complexes practically do not take part in acousto--defect interactions whereas divacancy neutron-- exposed structures and vacancy--interstitial oxygen pairs in γ--exposed structures can be effectively modified by applying USL. Thus, ultrasound can be an effective tool for controlling silicon structure characteristics.

The experimental investigation of ultrasound influence on the I-V characteristic of silicon n^+-p--structure has been carried out. The ultrasound induced effects in silicon structures, which have been exposed to reactor neutrons or 60Co gamma radiation, were studied too. The investigation revealed the acoustically driven reversible decrease of both the minority carrier lifetime in a structure base and the shunt resistance. The effect intensifies in irradiated structures. The analysis shows that the acoustically induced increase of carrier capture coefficient of point or extended defects is a reason of observed effects. It has been found out that the ultrasound loading leads to the reversible modification of SCR carrier lifetime and ideality factor. Changes are opposite in sign in non--irradiated and irradiated structures. The qualitative model of observed phenomenon, which is based on the increase of a distance between coupled defects or between defect complex components under ultrasound action, was considered. It has been shown that divacancy and pair vacancy--interstitial oxygen are effectively modified by ultrasound in neutron-- and γ--exposed structures respectively. Interstitial carbon--interstitial oxygen complex does not practically take part in acousto--defect interaction. Thus, ultrasound can be an effective tool for controlling silicon structure characteristics.

Tabs captions.

Tab I. The sample irradiation parameters.

Tab.II The ultrasound loading parameters.

Tab III. Characteristics of temperature dependences of n+-p--Si structure parameters.

Tab IV. Acoustically induced change of n+-p-Si structure parameters (at 330~K).

Tab V. Measured and estimated base lifetime parameters.

Tab VI. Cited and calculated defect parameters.

Figure captions

Fig.1 Dark I-V characteristics measured (a) at 306~K for non--irradiated (circles), neutron--irradiated (squares) and gamma--irradiated (diamonds and triangles) structures without USL; (b) at 301~K (circles) and 341~K (asterisks) with (filled marks, Ui--2) and without (open marks) USL for the iSC. The marks are the experimental results, the solid lines are the fitted curves using Eqs. (1)-(5). The dashed, dotted and dot--dashed lines in (a) represent the calculated base, SCR and shunt components of full (black solid line) iSC current.

Fig.2 SCR lifetime (a, left axis, open marks), base lifetime (a, right axis, filled marks), ideality factor (b, left axis, open marks) and shunt resistance (b, right axis, filled marks), obtained before, during and after USL at 330~K. Data for iSC (circles) and g7SC (triangles) are presented.

Fig.3. Temperature dependences of ideality factor for non--irradiated (curves 1--3, circles), neutron--irradiated (4--6, squares) and γ--irradiated (7--11, diamonds and triangles) samples. The curves 1, 4, 7 and 9 (open marks) are obtained without USL, curves 2, 3, 5, 6, 8, 10, and 11 correspond to Ui--1, Ui--2, Un--1, Un--2, Ug6--2, Ug7--1, and Ug7--2 respectively. The marks are the experimental results, the lines are the fitted curves using Eq.~(2).

Fig.4 Temperature dependences of SCR lifetime for non--irradiated (curves 1--3, circles), neutron--irradiated (4--6, squares) and $\gamma$--irradiated (7--11, diamonds and triangles) samples. The curves 1, 4, 7 and 9 (open marks) are obtained without USL, curves 2, 3, 5, 6, 8, 10, and 11 correspond to Ui--1, Ui--2, Un--1, Un--2, Ug6--2, Ug7--1, and Ug7--2 respectively. The marks are the experimental results, the lines are the fitted curves using Eq. (7).

Fig.5 Model of CDLR center behavior under US action.

Fig.6 Simulated dependencies of AI changes of coupling parameter on the vibration amplitudes. Axis|u\_D-u\_A| corresponds to δ=0 case, whereas axis |u\_D+u\_A| corresponds to δ=180 case. The parameters are set to a\_0=3.23 nm, r\_in=5 nm (open marks), 15 nm (semi--filled marks), and 25 nm (filled marks), φ=0 (circles), 90 (squares). Triangles correspond to mean ε\_RDA value for [0, 180] φ range.

Fig 7. Temperature dependences of base lifetime for non--irradiated (curves 1--3, circles), neutron--irradiated (4--6, squares) and $\gamma$--irradiated (7--11, diamonds and triangles) samples. The curves 1, 4, 7 and 9 (open marks) are obtained without USL, curves 2, 3, 5, 6, 8, 10, and 11 correspond to Ui--1, Ui--2, Un--1, Un--2, Ug6--2, Ug7--1, and Ug7--2 respectively.

Fig 8. Dependences of base lifetime relative change on US intensity for non--irradiated (circles), neutron--irradiated (squares), and γ—irradiated (triangles and diamonds) samples. Lines are the fitted curves using Eq. (19).

Fig 9. Temperature dependences of shunt resistance for non--irradiated (curves 1--3, circles), neutron--irradiated (4--6, squares) and γ--irradiated (7--11, diamonds and triangles) samples. The curves 1, 4, 7 and 9 (open marks) are obtained without USL, curves 2, 3, 5, 6, 8, 10, and 11 correspond to Ui--1, Ui--2, Un--1, Un--2, Ug6--2, Ug7--1, and Ug7--2 respectively. The marks are the experimental results, the lines are the fitted curves using Eq. (21)-(23).

Fig10. Permanent changes of SCR lifetime (a, squares), ideality factor (b, circles), base lifetime (c, triangles), and shunt resistance (d, asterisks) versus accumulated illumination time. Sample iSC, T=295 K. Filled, semi--filled and open marks correspond to sample before annealing, after first 10 min 200 C annealing, and after second 10 min 200C annealing, respectively.

Fig.11. SCR lifetime (a, squares, left axis), ideality factor (a, circles, right axis), base lifetime (b, triangles, left axis), and shunt resistance (b, asterisks, right axis) as a function of time since illumination stoping. Sample iSC, T=295 K. Lines are calculated by using Eqs.(25)--(26) and E\_DFe=0.63 eV (dash--dotted lines), 0.68~eV (solid lines), and 0.73~eV (dashed lines).